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Agent-based Training: Facilitating Knowledge and Skill Acquisition in a Modern Space Operations Team

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ABSTRACT

The U.S. Air Force is in the process of implementing a substantially larger role for space operations and a new operations system, the space-based infrared system (SBIRS), to accompany that role. Despite the increased responsibility that will accompany this new role and the implementation of SBIRS, increases in satellite operations personnel may not occur and if they do, they are unlikely to be commensurate with the increase in responsibility. In this effort we have identified SBIRS System Crew Chief (SCCH) task performance demands that are likely to be worsened by the pending increase in workload but which, if managed well, can reduce its negative impact. These task demands are event prioritization, task allocation, and team communications. In this paper, we describe the design stages and design of a training and performance support system called the Adaptive Decision Enabling and Performance Tracking Toolkit (ADEPTT) that will assist the SCCH manage team coordination and perform the aforementioned tasks in particular during high workload periods. ADEPTT will be built using a cognitive agent architecture and will have four major components – supervisory agents, an instructional agent, a crew communication tool, and synthetic teammates – in order to provide comprehensive training and performance support. It is our goal to build ADEPTT so that it is maximally supportive, minimally obtrusive, has a minimal learning curve, and integrates easily into current training and operations. In designing this toolkit, we followed human-centered design principles, taking into account the demands and limitations operators already face, and being careful to not add to existing problems such as limited display space. This required us to work closely with members of the SBIRS operational community and make use of research tools such as cognitive task analysis methods to obtain information that is critical to successful human-centered design and improved efficiency. It is our hope that this tool, once it is built and implemented, will continue to be expanded and refined to meet the training and performance support needs of the SBIRS and other crews as satellite operations become increasingly complex.

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15. SUBJECT TERMS

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In response to current trends -- the end of the Cold War, the asymmetric threat environment, and technological advances, in particular – the U.S. military is in the process of modernizing its objectives, priorities, tactics, equipment, and infrastructure. As a part of this modernization, the U.S. Air Force has called for and is in the process of implementing a substantially larger role for space operations. This larger role will encompass significantly greater responsibility. It will move space warfighters off the sidelines from where they have, in the past, been limited to monitoring for the occurrence of a limited set of events. In future space operations, space warfighters will find themselves on the playing field – critical participants in tactical operations.

To succeed in this new role, space warfighters require a new space operations system. This system, the Space-Based Infrared System (SBIRS), will consist of two subsystems, SBIRS-High and SBIRS-Low. Change will not be limited to the space warfighter's equipment, however – space personnel will be required to undergo substantial change as they adapt to their new role and new equipment. For some operators, the implementation of SBIRS will require them to learn very different ways of doing their job, if not entirely new jobs. All operators, however – regardless of whether their basic responsibilities have changed – will be affected by a dramatic increase in workload associated with an increase in the number of satellites and with the urgency of supporting tactical operations in real time.

Steps currently are being undertaken to address the training and performance support requirements that may accompany this imminent expansion of space operations. In this particular effort, we are looking at both training and performance support solutions that would help crew chiefs and crew commanders manage their crews' effectiveness in high workload situations. Although the solutions we design will be applicable to all senior positions (i.e., crew chiefs and crew commanders), in this early phase of design we are focusing on just one senior SBIRS position – the Systems Crew Chief (SCCH).

In the section below, we discuss our general approach to assessing the training and real time performance support needs of the SCCH. Then we describe the SCCH position and the crew for which he/she is responsible, the challenges they will face as more and more SBIRS satellites come on line, our proposed training and performance support solution designs, and human-centered design considerations. Finally, we conclude by describing implications of the solutions for contributing to the effectiveness of other types of satellite operations crews.

General Approach

An important principle of training and support system design is to design with the goal of helping task performers overcome information processing limitations that make performance vulnerable to error and inefficiency (e.g., Andriole & Adelson, 1995; Morrison, Kelly, Moore, & Hutchins 1998; Zachary, 1988). For example, a decision support system designed for crime solving might target the memory recall limitations and information processing biases shown to affect eyewitness accounts of events such as robberies and automobile accidents (e.g., Loftus, 1989). Other limitations that a training or performance support system might target include working memory capacity, the speed with which people can perform cognitive operations, attentional limitations, and multi-tasking limitations. Finally, these systems might be designed to compensate for a lack of specialized skill associated with high-turnover jobs, or jobs

through which personnel are cycled, as is often the case in the military.

In addition to helping task performers overcome challenges such as these, it often is important that a support system support the acquisition of expertise. That is, it should help the task performer understand domain concepts and dynamics and support their development of strategies and skills.

Key challenges in designing training and performance support systems are identifying the ways in which a person's performance may be limited and determining how a computer-based technology can best help the person overcome or circumvent the identified limitations. These design challenges and a recommended design approach are described by Zachary (1988). Key to this approach is access to subject matter experts (SMEs) to both inform the system's structure, logic, and content and to assess the system in terms of its usability.

Specifically, Zachary recommends the developer work with task performers to first define the highest level of goal events – the conditions that task performers are trying to achieve during the course of performing their jobs. In addition, he suggests defining one more level of goals – the subgoals beneath those goal events. These initial steps play the important role of specifying both a focus for the system (i.e., supporting specific goals) and a framework that is consistent with the way task performers approach their job. Next, Zachary recommends that the developer analyze task performance in terms of (1) the context of task performance and associated demands and limitations and (2) the cognitive processes used to perform the task and cope with the demands and limitations. Then, the developer should identify those cognitive processes that represent 'weak links', where the task performer may falter or use an ineffective heuristic. These cognitive processes become the targets of the support system.

Once the targets of the system are identified, the developer determines which support technologies are most appropriate. In the present effort, we considered each of the types of support listed below and identified by Zachary (1988):

- Representation aids that help the operator conceptualize complex relationships, changes across time, or large amounts of data that surpass working memory capacity;
- Process models that assist with choosing among multiple courses of action;
- Value models that help the operator assess multiple decision factors or attributes;
- Data management tools that help the operator structure and sort through all data available in a complex problem;
- Knowledge management tools that supplement the operator's knowledge base;
- Automated reasoning techniques that perform intermediate analyses that the operator tends to perform ineffectively as part of a larger decision process; and
- Decision structuring tools designed to support 'single-instance' decisions.

After following the steps above, the support system developer should be ready to build the information content, logic and outputs of the system. This step, like the ones before it, relies heavily on access to SMEs and ideally makes use of one or more cognitive task analysis techniques, which are well suited to capturing cognitive processes, strategies, knowledge, and the dynamic ways in which these task elements guide performance.

Training and Performance Support Needs

In order to identify goals, subgoals, demands, and limitations, we relied heavily on the space operations community for information. Demanding work schedules associated with bringing a new operations system on line limited our access to personnel. Therefore, we have relied extensively on one person – a senior space operations expert in a training position – and obtained additional opinions and guidance from two former members of space operations teams. The following two paragraphs contain high-level information

about the SCCH task, including information about goals and team context, obtained while working with these SMEs.

The SBIRS SCCH oversees and coordinates the satellite systems crew. The satellite systems crew consists of two satellite systems operators (SSOs) and three ground system operators (GSOs). Together, the SCCH and crew have the overall responsibility of keeping satellites healthy. The SCCH and SSOs are specifically responsible for tracking and commanding satellites, monitoring their health, diagnosing anomalies, and correcting anomalies. The GSOs support the SCCH, SSOs, and other SBIRS crews by establishing and maintaining communications links with the satellites and other operations centers.

Although the SCCH is in control of satellite systems operations, the SBIRS Crew Commander oversees both the SCCH and the Mission Crew Chief (MCCH). However, the MCCH is the Crew Commander's primary interest and the SCCH is relatively autonomous, at least in the current operations center configuration. The MCCH and mission crew are responsible for analyzing data collected via satellite, influencing the data collection process, and disseminating data to operations centers. They interact with the systems crew infrequently and these interactions mainly are limited to requests for the GSOs to fix or adjust datalinks.

Currently, the job of the satellite systems crew involves relatively mundane monitoring and straightforward commanding interspersed with time pressured anomaly diagnosis and resolution. Scheduled commanding sessions also can be time pressured due to the limited window of time available. As the SBIRS system comes to be fully implemented, this situation will change. In particular, the job will come to be much more characterized by time pressured anomaly resolution and commanding and less by mundane monitoring.

In addition to assessing SCCH goals and task performance context, our analysis identified demands and limitations currently placed on the SCCH. These include:

- A large information load – operators receive hundreds of pieces of information about multiple satellites
- Limited screen space for displaying the large amount of information they receive
- A requirement for continuous monitoring/vigilance
- When action is required, it typically is time critical in that it must be executed at a specific time and within a limited window
- Mistakes, such as failure to detect an anomaly in a timely manner or transmission of an incorrect command, can have extremely costly consequences
- Many tasks require coordination among crew members, but no mechanisms for facilitating that coordination exist; crew members who are not seated next to each other coordinate by hollering to one another

Perhaps with the exception of the last item in the above list, system design features and operator strategies have been developed to address SCCH task performance demands and limitations. For example, to help them cope with both the large amount of information and the limited display space, operators can create personalized information displays that contain only the most informative and diagnostic pieces of information. This helps them monitor and quickly find the information they most frequently need. As another example, to minimize mistakes, procedures have been developed whereby no command is transmitted to a satellite until a second crew member has first checked it. Thus, of the demands and limitations listed above, we are focusing only the last. This item, which deals with team communication, will be even more of a problem once SBIRS is fully implemented.

Once the full complement of SBIRS satellites is on line, many of the demands and limitations identified in the list above will be exacerbated by the increased workload. The SCCH and other crew members in leadership roles will be faced with coordinating the task performance of crews that have to deal with significantly more task demands and demands that frequently overlap. Currently, crew leaders do not

have strategies or tools to help them coordinate their crews to deal effectively with multiple concurrent events. For example, they do not have strategies or tools to help them prioritize events or delegate tasks in a high workload environment.

It might be argued that additional steps could be taken to improve the designs and procedures that are currently in place. However, we have chosen to focus on the future – specifically, on facilitating team coordination under the anticipated high workload conditions associated with the pending growth in operations. Tools designed for this future situation will have maximal impact because current operator strategies and system design features for the most part do not accommodate future coordination requirements. Furthermore, increasing numbers of satellite operations teams will face team coordination challenges as advances in satellite and communications technologies and increases in the role of space require them to grow in size and complexity and interact with more and more external teams.

Training and Performance Support Solutions

To assist the SCCH with managing and coordinating the satellite systems crew, we are designing a crew coordination support toolkit designed to overcome challenges associated with the increased workload SBIRS operators will soon experience. The specific challenges the tool addresses are prioritizing events, delegating tasks to crew members, and effective team communication. This toolkit initially will be used to support training. However, it will be equally capable of supporting performance during real time operations. This toolkit, called the Adaptive Decision Enabling and Performance Tracking Toolkit (ADEPTT), will consist of data and knowledge management tools and automated reasoning techniques. The specific components of the ADEPTT design are:

- supervisory agents that detect anomalies and other events, prioritize them, monitor SSO and GSO availability, and recommend task delegations;
- a crew communication tool featuring task performance shortcuts (e.g., ready-to-go command strings) that enables the SCCH to communicate with the GSOs and SSOs using a keyboard and mouse;
- an instructional agent that monitors SCCH performance (e.g., prioritization and delegation) and that provides the SCCH feedback at the end of a training scenario; and
- synthetic teammates that will take on the role of GSOs and SSOs, and thereby make SCCH training possible in the absence of live team members.

ADEPTT will rely heavily on cognitive agent technology – this technology is used to build and 'give life to' the synthetic teammates as well as the supervisory and instructional agents. The cognitive agent technology we are using is CHI Systems' iGEN. The iGEN™ cognitive agent development software, (Zachary, Ryder, Ross, and Weiland, 1992) provides both an architecture for building synthetic teammates and agents and an execution engine that allows the them to interact in real time with users in a computer-based work or training environment. In effect, iGEN™ is used to build a model of cognitive task performance and transform it into an executable agent. IGEN™ also provides various tools to support the creation and modification of the cognitive model, as well as an Application Program Interface (API), which we call the agent's shell, for communicating with simulation and computer-based work environments.

The cognitive architecture and modeling framework embodied by iGEN™ is influenced principally by the work of Alan Newell (e.g., Card, Moran, & Newell, 1983; Newell, 1990). In its simplest form, Newell's Unified Theory of Cognition breaks human information processing into three parallel macro-level mechanisms – perception, cognition, and motor activity – and attempts to characterize them in terms of general principles derived from years of cognitive science research. Consistent with Newell's theory, iGEN™ includes mechanisms that represent perception, memory, decision-

making, and action and links these mechanisms in ways consistent with cognitive principles about how information is stored, retrieved, and used, and how these processes are affected by resource limitations.

This type of architecture makes it possible to represent human expertise in a comprehensive way that is consistent with what we know about cognition and how cognition drives task performance. Further, iGEN™ has been used successfully in a number of projects in which intelligent training support or synthetic teammates were called for (e.g., Ryder, Deaton, Stevens, & Comptois, 1998; Zachary, Ryder, & Hicinbotham, 1998; Zachary et al., 2001). We assert that by using this type of architecture, the ADEPTT synthetic teammates and agents will be particularly well-suited to mimicking, tracking, assessing, and supporting cognitive task performance.

In the sections that follow, we describe each of the four main components of ADEPTT in more detail and then describe the human-centered design principles that are guiding the development of ADEPTT.

Supervisory agents. These cognitive agents will be built using data and findings obtained during a cognitive task analysis of the SCCH and satellite systems crew member jobs. They will be able to recognize a wide array of situations, process a large number of situation parameters, make complex decisions about event priorities and task delegations, determine appropriate actions, and make the relevant information, diagnoses/conclusions, and action sequences available to the crew chief or operator. As noted above, these agents will detect anomalies and other events, prioritize them, monitor SSO and GSO availability, and recommend task delegations. During training exercises, the agents will serve as guides that support the SCCH in making correct decisions or they may be deactivated so that the SCCH is on her own. When ADEPTT is transitioned from training to operations, these agents will similarly act as guides, although their purpose will be to support SCCH performance rather than assist with training. Their outputs will be shown in a single display window that can be manipulated to utilize minimal display space.

By building expert knowledge into these agents, they will be able to recognize and respond to a majority of events. However, just as humans – even those who are considered experts in a domain – can encounter an unfamiliar or new situation, the ADEPTT agents will not recognize every possible situation. Thus, they will be programmed to respond to such cases appropriately. Specifically, in these cases, the agents will provide the SCCH or operator with as much information as they are able without making recommendations that are contingent on an accurate assessment of the situation (e.g., task delegation recommendations).

Crew communication tool. Currently, satellite systems crew members communicate verbally to one another, and this includes hollering in order to convey information to someone working in another part of the room. As the workload of this crew increases, reliance on this mode of communication will become increasingly problematic. The crew communication tool will be designed not to completely replace verbal communications, but to facilitate communications. The tool also will be critical to the effectiveness of the supervisory agent described above. This agent will need to monitor commands passed from the SCCH to crew members in order to evaluate SCCH performance and guide SCCH training (although it is possible to build cognitive agents that recognize verbal commands, modern speech recognition technology is not sufficiently reliable to make this an appealing option).

This tool will allow the SCCH to select, via mouseclicks, simple command strings such as 'prepare to command' and 'configure system for commanding' along with the satellite of interest and send them to a particular crew member by clicking on his/her icon. In addition, it will allow the SSOs and GSOs to send, via mouseclick, frequently used communication strings, for example, to accept a task delegated by the SCCH, to inform the team that an anomaly

is resolved, to request help, or to bring a new anomaly to the attention of the SCCH.

The crew communication tool will utilize the underlying cognitive agent architecture of ADEPTT to provide situated communication support. Specifically, supervisory agents will detect and evaluate situations and crew availability. In the context of the communication tool, the agents will use this information to offer complete command strings to the SCCH that can be sent to an available crew member with a single mouseclick or keypress.

Instructional agent. The instructional agent, as in the case of the supervisory agents, will be built using data obtained from a cognitive task analysis. This agent will have the same general types of capabilities as the supervisory agents, however it will use those capabilities differently. This agent will use its knowledge about the SCCH job, crew activities, and the constantly changing environment to evaluate SCCH response times and the accuracy of SCCH decisions, actions, and communications. At the completion of a training scenario, the instructional agent will make available to the SCCH and training personnel accuracy measures, response time measures, process measures (e.g., did the SCCH delegate tasks effectively?) and the overall outcome of the situation (e.g., how much propellant was lost before the leaking tank was isolated?). In addition, the agent will make available the performance standards the SCCH should endeavor to meet and will offer tips about aspects of performance on which the SCCH should focus during the next training exercise and about how to improve performance.

Synthetic teammates. The SCCH will be able to activate SSO and GSO synthetic teammates to participate in training exercises when some or all of the systems crew is unavailable. This capability will become increasingly important as satellite systems operations become more sophisticated, increasing the need for training, and as crew workload increases, making it less likely that a full set of crew members will be available at any given time for training. Synthetic teammates additionally will contribute to SCCH training by acting in ways that pose realistic challenges to the SCCH. For example, they might commit anomaly diagnosis or commanding errors, fail to communicate an important piece of information, not be able to find the correct command plan in a timely manner, or find themselves unable to keep up with a large number of taskings. This capability of the synthetic teammates is important in light of the assertion that expertise is gained through experience with a variety of challenging, and nonroutine events (e.g., Klein, Calderwood, & MacGregor, 1989; Salthouse, 1991; Schmidt & Bjork, 1992).

The ADEPTT synthetic teammates will be similar to live teammates in that their performance will be dependent on their access to data and information and they will change their behavior appropriately given detected changes in the task environment. Further, because they will perform tasks using the same information and logic as a human, they will be prone to the same types of performance errors. They will respond to commands received from the SCCH and task-performance related requests from one another or other live teammates (e.g., a request to verify a command before a teammate sends it to a satellite). Similarly, they will be able to send information such as the results of a commanding session, acknowledgement of a command, or verification of a command to the SCCH and other teammates.

Design Principles

The design of this tool is guided by human-centered design guidelines. In particular, ADEPTT is designed to build and support expertise. Expertise is characterized by the development of efficient and goal-focused knowledge and job performance strategies. Accordingly, ADEPTT is designed to support efficient goal-focused performance without interfering with experts' ability to adapt their own personalized strategies. One of the design guidelines we are following is the mapping principle, which holds that goal-related data should be incorporated into higher-level functional representations that are mapped directly to salient perceptual properties of the display (Woods, 1991). In keeping with this principle, we are

highlighting organizing toolkit functionality around main goals, such as anomaly resolution.

In addition, we are designing ADEPTT to be flexible – each display and function within the toolkit will be accessible from multiple points in task performance and linked to multiple displays. For example, the toolkit will feature direct links between alerts and response procedures. Through the use of tailored links and goal-focused display design, information will be accessible with minimal effort. ADEPTT will exhibit additional flexibility by allowing users to disable functions within the toolkit – for example, users will be able to disable the instructional agent and synthetic teammates, and can elect to not be shown particular outputs generated by the supervisory agents.

Finally, our design is influenced by a prudent trend toward the increased use of critiquing systems (e.g., Guerlain et al., 1999) to provide performance and decision support. Because expert systems do not produce optimal responses in all situations and can occasionally steer decision makers down the wrong path, many support system developers are using techniques that are supportive of users while minimally interfering with their performance. These techniques include improved access to data, data synthesis, and the evaluation, or critique, of users' decisions and performance, accompanied by guidance or feedback.

Conclusions

Despite the increased operator workload that will accompany the implementation of SBIRS, increases in satellite operations personnel may not occur and if they do, they are unlikely to be commensurate with the increase in workload. In this effort we have identified SCCH and crew task performance demands that are likely to be worsened by the pending increase in workload but which, if managed well, can reduce its negative impact. These task demands are event prioritization, task allocation, and team communications. In the section above, we described a toolkit, ADEPTT, which we have designed and will be building in order to support the SBIRS SCCH with the performance of these tasks.

It is our goal to design ADEPTT so that it is maximally supportive, minimally obtrusive, has a minimal learning curve, and integrates easily into current training and operations. In designing this toolkit, we are taking into account the demands and limitations operators already face and are being careful to not add to existing problems such as limited display space. This required us to work closely with members of the SBIRS operational community and make use of research tools such as cognitive task analysis methods to obtain information that is critical to successful human-centered design and improved efficiency.

It is our hope that this tool can be expanded and refined to meet the training and performance support needs of the SBIRS satellite operations crew as their work becomes increasingly complex. ADEPTT may prove useful in SBIRS mission control operations as well – the mission operations crew similarly will experience significantly increased workload levels once SBIRS is fully implemented. In addition, we anticipate that portions of ADEPTT, such as the situated communications support or certain supervisory agents will be directly applicable to satellite crews in a number of satellite control organizations.

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